Chapter 14 Energy from Nuclear Science

The isotope ^{235}U, with an abundance of only 0.7% in natural uranium, is commonly used to produce electricity in nuclear fission reactors**.** This isotope has the distinctive and useful property of undergoing nuclear fission through interaction with thermal-energy neutrons (neutrons with average speeds of only a few km/s). The other main isotope of uranium, ^{238}U, does not undergo nuclear fission with thermal neutrons, but it does capture neutrons to form the isotope ^{239}Np which then decays to ^{239}Pu. This isotope of plutonium undergoes nuclear fission with thermal neutrons with a higher probability than that of ^{235}U. The energy released in the fission of ^{235}U and ^{239}Pu, mainly in the form of kinetic energy of the fission fragments, provides the heat to run the turbines that generate electricity at a nuclear fission power plant.

Nuclear Fission Energy

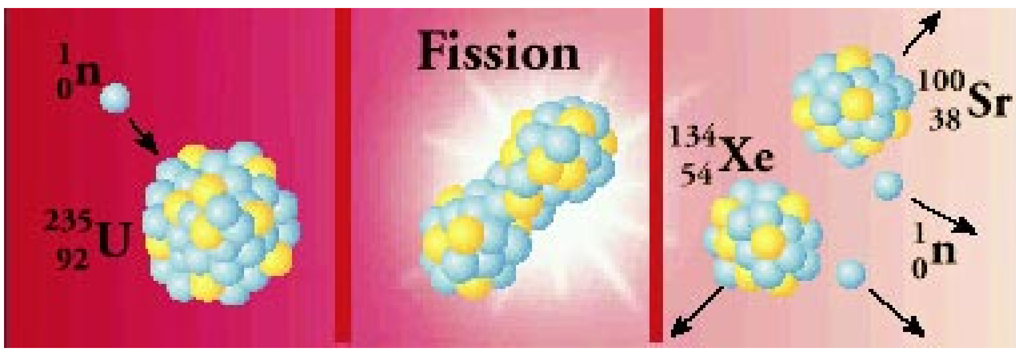

Fig. 14-1. Fission of ^{235}U after absorption of a thermal neutron.

The relevant nuclear reactions can be written as follows:

$$^{235}U + {^1n} \rightarrow \text{fission products + neutrons + energy (\sim 200 MeV)} \quad (1)$$

$$^{238}U + {^1n} \rightarrow {^{239}U} + \text{gamma rays} \quad (2)$$

$$^{239}U \rightarrow {^{239}Np} \rightarrow {^{239}Pu} \qquad \text{(a series of beta decays).} \quad (3)$$

An integer number of neutrons, for example, either two, three or four, are emitted in the reactions leading to different pairs of fission products described in reaction (1). The average number is 2.43. Some of the neutrons in reaction (1) can be used to induce fission in another ^{235}U nucleus, thus continuing a controlled, self-perpetuating nuclear chain reaction. Some fraction of the remaining neutrons from reaction (1) are utilized in reaction (2) to produce ^{239}Pu. The rest are absorbed in other nuclei without further effect.

The isotope ^{232}Th, although not fissionable with thermal neutrons, is a possible energy source because it absorbs thermal neutrons to produce long-lived ^{233}U, which also undergoes thermal neutron fission with a high probability. Thus the "big three" readily fissionable nuclei are: ^{235}U, ^{239}Pu, and ^{233}U.

Fig. 14-2. The reactor vessel of a commercial reactor is inside this containment building.

A typical pressurized (or boiling) water nuclear reactor consists of a core of fissionable material (UO_2, enriched to 3.3% to 4% in ^{235}U) in which the chain reaction takes place. A picture of a reactor is shown in Fig. 14-2. The energy released in the fission process, which is primarily in the form of the kinetic energy of the fission fragments, heats the water. The water serves both as a neutron moderator (it slows down the fission neutrons to thermal energies), and as a heat transfer fluid. The chain reaction is controlled by rods of neutron-absorbing material inserted into the core. The thermal energy is removed from the core by the water to an external thermal-energy converter. In the pressurized water reactor (PWR), the thermal energy produces steam for the turbine through the use of a heat exchanger, whereas in a boiling water reactor (BWR), the steam is produced for direct use in the turbine.

Nuclear reactions liberate a large amount of energy compared to chemical reactions. One fission event results in the release of about 200 MeV of energy, or about 3.2×10^{-11} watt-seconds. Thus, 3.1×10^{10} fissions per second produce 1 W of thermal power. The fission of 1 g of uranium or plutonium per day liberates about 1 MW. This is the energy equivalent of 3 tons of coal or about 600 gallons of fuel oil per day, which when burned produces approximately 1/4 tonne of carbon dioxide. (A tonne, or metric ton, is 1000 kg.)

Nuclear reactors manufacture their own fuel, since they produce ^{239}Pu from ^{238}U. With the total worldwide installed nuclear capacity of 3.4×10^5 MW_e (megawatt electrical), one can estimate that more than 100 tonnes of ^{239}Pu are produced each year in reactors whose primary energy source is the fission of ^{235}U. This ^{239}Pu can be reprocessed from used fuel rods and used to power other reactors.

It is actually possible to generate more ^{239}Pu than is used up in the reactor by surrounding the core with a uranium blanket and generating ^{239}Pu in this blanket. This is called a breeder reactor. A breeder reactor needs to be operated with fast neutrons, a so-called "fast breeder" reactor. In a fast-breeder reactor, water cannot be used as a coolant because it would moderate the neutrons. The smaller fission cross sections associated with the fast neutrons (as compared with thermal neutrons) leads to higher fuel concentrations in the core and higher power densities, which, in turn, create significant heat transfer problems. Liquid sodium metal may be used here as a coolant and heat-transfer fluid. Only one fast breeder reactor, the French Superphénix, is currently operational and it has experienced significant problems during its operation. Research on breeder reactors has essentially stopped in the United States because of concerns over nuclear proliferation since the plutonium bred in the reactor might be used for making weapons. Due to such concerns and the complexities of construction and operation, it is unlikely that breeder reactors will ever come into general operation.

In a yearly operating cycle of a typical (1000 MW_e) pressurized water reactor, the spent fuel contains about 25 tonnes of uranium and about 250 kg of ^{239}Pu. Some 40% of the energy produced in the course of a nuclear fuel cycle comes from ^{239}Pu. Since 22% of the electricity generated in the United States comes from nuclear power plants, about twice as much electricity is generated from ^{239}Pu as is generated from oil-fired electrical generating plants.

Some 435 nuclear power plants operating around the world generate about 345,000 MW_e of electricity in 35 countries, nearly one-fifth the world's electricity supply. Some countries depend vitally on the electricity generated by nuclear energy. France generates 76% of its electricity from nuclear power plants; Belgium—56%, South Korea—36%, Switzerland—40%, Sweden—47%, Finland—30%, Japan—33%, and the United Kingdom—25%. Bulgaria generates 46% of its electricity from nuclear power, Hungary—42%, and the Czech Republic and Slovakia combined—20%. Although the United States is not a leader in percentage, it has the largest total electric output from nuclear power: 99,000 MW_e from 109 plants, generating 22% of U.S. electric power.

However, the United States, which led the world in early nuclear electric power development, was also first to be affected by its decline. Over the past decades the U.S. nuclear electric power industry has received no new domestic orders due to concerns over reactor safety, waste disposal, regulatory uncertainty, increased costs, and decreased electrical demand growth. These same pressures are now affecting nuclear power worldwide, although countries such as France and South Korea still have vigorous programs. A rebirth may be imminent because of impending solutions to some of these problems and because of the problem of global warming due to the release of greenhouse gases in the combustion of fossil fuels.

The public has become suspicious of nuclear energy partly because of the elaborate methods used to address safety concerns. Most worrisome is the need for external electrical power to supply the pumps used in emergency core cooling systems in the types of reactors now used in the United States. In an accident, this external supply could possibly be disrupted leading to a release of radioactivity. New reactor designs use passive safety to address this problem. Passive safety features can be thought of as characteristics of a reactor that, without operator intervention, will tend to shut or cool a reactor down, keep it in a safe configuration, and prevent release of radioactivity. These features fall into two broad categories—features that are designed to prevent accidents, and those that mitigate the effects of accidents. Many current problems arise from the huge scale of reactor construction projects. Typically, 1000 MW reactors have been constructed on site. The new types of reactors are smaller (e.g. 600 MW) and may be constructed in factories where uniformity and quality control can produce reactors and operating procedures less prone to failure. Examples of these new designs are two types of Advanced Passive Light Water Reactors (APLWRs), the Liquid Metal Reactor (LMR), and the Modular High Temperature Gas-cooled Reactor (MHTGR). The APLWR is the most developed of these new reactor types. Both the AP-600 (Advanced Passive 600 MW_e), a pressurized water reactor, and the SBWR (Simplified Boiling Water Reactor) are 600 MW_e in size, run at lower temperatures and with larger water inventories than current light water reactors, and have passive emergency core-cooling systems that utilize gravity. They both use passive natural circulation for the removal of heat from the core.

Nuclear fission reactors, usually pressurized water reactors with energy conversion based on a steam-turbine cycle, have been used extensively to power ships. The United States has built and launched an impressive number of nuclear powered ships—a total of 155 attack and missile submarines, 9 guided missile cruisers (18 reactors), and 5 aircraft carriers (with a total of 24 reactors) and has operated 9 prototype reactors on land. Of this total, 22 submarines have been decommissioned or are non-operational. Shipboard reactors are constructed smaller than similar installations ashore, with special attention given to maintenance, protection from collision, and leakage. Although the primary use of nuclear power has been in submarines and other military vessels, a few non-military marine installations have been demonstrated. Examples include the Russian icebreaker Lenin and the United States demonstration merchant ship NS Savannah.

Nuclear Fusion Power

Nuclear fusion reactors, if they can be made to work, promise virtually unlimited power for the indefinite future. This is because the fuel, isotopes of hydrogen, are essentially unlimited on Earth. Efforts to control the fusion process and harness it to produce power have been underway in the United States and abroad for more than forty years.

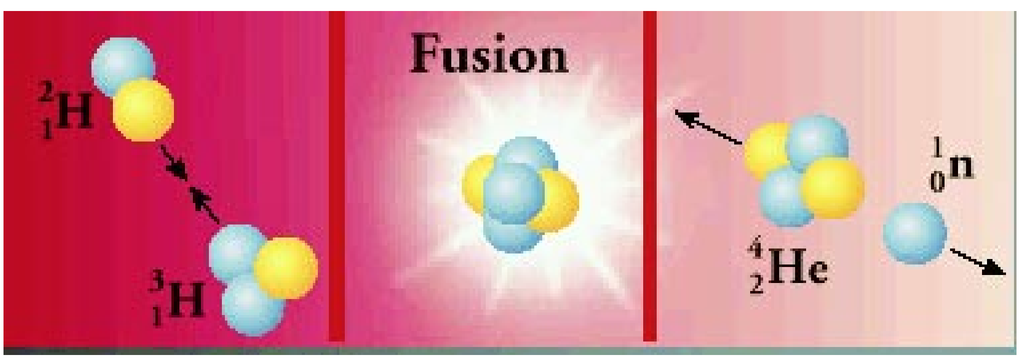

Fig. 14-3. A diagram showing a typical fusion reaction.

Nuclear fusion is the source of energy in the sun and stars where high temperatures and densities allow the positively-charged nuclei to get close enough to each other for the (attractive) nuclear force to overcome the (repulsive) electrical force and allow fusion to occur. Fig. 3 shows one fusion reaction. The most promising fusion reaction,

$$^{3}H + ^{2}H \rightarrow ^{4}He + n + 17.6 \text{ MeV}$$

involves the radioactive nuclide tritium (^{3}H), available from the nuclear production reaction

$$^{6}Li + n \rightarrow ^{3}H + ^{4}He.$$

To produce energy using this reaction, both the magnetic confinement reactor with a high temperature plasma (a gas that has been completely ionized) and the inertial confinement reactor (which utilizes laser implosion technologies) have been investigated. Extremely high plasma temperatures are required in the magnetic confinement reactor and difficult laser implosion techniques are required for the inertial confinement reactor. Although significant progress has been made in these investigations, no working reactor that produces more energy than it consumes has been built. Unfortunately, the funding for continuing this work has declined, and the work is proceeding at a slower pace.

Although these types of reactors would not have the fission product waste disposal problem of fission reactors, fusion reactors generate large number of fast neutrons, leading to large quantities of radioactive byproducts.

Another approach to nuclear fusion—an approach that could lead to aneutronic power (power without neutrons) and non-radioactive nuclear energy—uses the concept of colliding-beam fusion (CBF). One aneutronic method features the ^{2}H + ^{3}He reaction leading to the products ^{1}H + ^{4}He. However, this requires ^{3}He as fuel and terrestrial sources of this are limited. The Moon is a potential source of ^{3}He produced by cosmic-ray protons hitting the Moon directly and not being absorbed by an atmosphere as on Earth. Another potential approach for colliding beam fusion is the ^{11}B + ^{1}H reaction leading to the three ^{4}He nuclei. The energy release is in the form of charged particles whose kinetic energy can be converted to electricity with a very high efficiency. No other available source of energy comes close to this degree of cleanness and efficiency. In all current energy sources, approximately two-thirds of the energy is lost in the form of waste heat or thermal pollution. In the CBF approach, there is virtually no waste. This design favors small size for the greatest efficiency (100 MW_e or less), and would lead to either power plants with several reactors or decentralization of energy production.